View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Elsevier - Publisher Connector

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 102 (2015) 714 – 721

Procedia Engineering

www.elsevier.com/locate/procedia

The 7th World Congress on Particle Technology (WCPT7)

Thermal radiation contribution to metal dust explosions

Rim Ben Moussa[a,b]*, Mohamed Guessasma[a], Christophe Proust[c], Khashayar Saleh[b], Jérome Fortin[a]

[a]*Laboratoire des Technologies Innovantes, LTI- EA 3899, University of Picardie Jules Vernes, 02100 Saint Quentin, France*
[b]*Laboratoire des Transformations Intégrées de la Matière Renouvelable, TIMR- EA 4297, University of Technology of Compiègne, 60200 Compiègne, France*
[c]*Institut National de l'EnviRonnement industriel et des rISques, INERIS, DRA-PHDG, 60550 Verneuil-en-Halatte, France*

Abstract

Despite the significant progress made towards the understanding of flame propagation mechanisms in dust-air mixtures, dust explosions still have a frequent occurrence and their danger presents a continuous threat to industries that produce, use and treat solid powders and dusts of combustible materials. In fact, many physical aspects are still needed to be clarified given the major difference existing between flame propagating in gaseous mixtures and in suspensions and many questions are still unanswered regarding the reasons behind the violence of fine metal dust explosions. Few experimental observations and theoretical considerations emphasized the potential role of radiation heat transfer in the behaviour of dust clouds' flames in which acceleration in flame propagation speed and instabilities were observed. Unfortunately, only few information is available, so far, concerning the capacity of radiative transfers of taking part in the propagation process. While investigating radiation phenomenon in dust clouds, we are faced with a complicated problem difficult to model analytically. The development of numerical approach, based on discrete element method (DEM), in order to treat this problem, seems more convenient. MULTICOR code, developed at the LTI, has already succeeded at modelling heat transfer in a bed of particles. Under this work, radiative heat transfer exchanged between particles in suspension is successfully calculated and we propose an original method of calculating heat transfers between dust and gas in the preheat zone of the flame. We are currently working on adapting the radiation models implemented to the case of fine particles and taking into consideration light scattered. With the purpose of determining the flame propagation speed and improving the knowledge of the phenomena involved, it would be possible to contribute to the development of suitable means of

* Corresponding author. Tel.: +3-364-623-9153.
E-mail address: rim.ben-moussa@utc.fr

1877-7058 © 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Selection and peer-review under responsibility of Chinese Society of Particuology, Institute of Process Engineering, Chinese Academy of Sciences (CAS)
doi:10.1016/j.proeng.2015.01.172

prevention and mitigation of dust explosion hazard.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Selection and peer-review under responsibility of Chinese Society of Particuology, Institute of Process Engineering, Chinese Academy of Sciences (CAS)

Keywords: Dust explosions ; flame propagation ; thermal radiation ; discrete element method (DEM).

1. Introduction

Given the frequency of dust explosions and their destructive potential, they are considered a major technological risk which now holds the attention of governments as well as the industrial sector so that an entire security engineering level was developed around this aspect.

There has been a gradual evolution in the prevention and mitigation of dust explosions over the past twenty years. This evolution is the result of a better understanding of the phenomena involved, namely the propagation of the flame through dust clouds [12], properties and characteristics of dust explosion [4], the ignition and the combustion time of particles [12, 9] and the size and concentration of particles [1, 2]; the flame front structure is proved to be strongly dependent on the particles' concentration [8].

The propagation of the flame in dust clouds is induced by thermal conduction from the burned products to the reactants through the combustion zone; this process is close to flames propagating in gaseous mixtures [12]. However, a major difference can exist between flame propagating in gaseous mixtures and in suspensions seen that the thermal radiation can contribute significantly to the heat transfer from the flame to the unburned cloud depending on the material of the particles. This contribution is related to the fraction of energy transmitted by radiation by the solid residues present in the combustion zone and which could heat up the particles of the reactive suspension [13].

Knowing that all the concepts of prevention and protection are based on the conduction-combustion flame model, should these means still be considered valid and useful? In order to answer this question and to succeed in proposing alternatives, additional work is needed to investigate the role of thermal radiation in the development of dust explosions.

Nomenclature

A_i, A_j	surfaces of particles Ω_i and Ω_j	m
C_d, C_{d0}	dust cloud concentration: at any x-plane; at input	$kg.m^{-3}$
C_p, C_{pg}	constant pressure specific heat: of dust; of the ambient gas	$J.kg^{-1}.°K^{-1}$
d_p	particle diameter	m
F_{ij}	view factor from the surface of Ω_i to the surface of Ω_j	
F_{iR}, F_{jR}	view factors from the surfaces of particles Ω_i and Ω_j to their surrounding medium	
I, I_f	radiation intensity: at any x-plane; at the flame front	$W.m^{-2}$
L_{ign}	ignition distance	m
r_p	particle radius	m
S_u	Flame propagation speed	$cm.s^{-1}$
T_{ad}, T_0	adiabatic flame temperature; temperature at input	°K
T_d, T_g	temperature: of a dust particle; of the ambient gas	°K
T_i, T_j	temperature: of particle Ω_i; of particle Ω_j	°K
T_{ign}	ignition temperature of a dust particle	°K
t	time	s
t_{ign}	ignition time	s
v, v_0	velocity of dust cloud: at any x-plane; at input	$m.s^{-1}$
x	distance	m
x_f	flame front position	m

α_g	thermal diffusivity of the ambient gas ($= \lambda_g/\rho_0 C_{pg}$) ....m^2.s^{-1}
Δt	time step ....s
ε_i, ε_j, ε_f	emissivity: of particle Ω_i; of particle Ω_j; of the flame
λ_g	thermal conductivity of the ambient gas ....W.m^{-1}.°K
σ_s	Stefan-Boltzmann constant = 5.6704.10^{-8} W.m^{-2}.°K
ρ_g, ρ_0	gas density: at any x-plane; at input ....kg.m^{-3}
ρ_p	solid particle density ....kg.m^{-3}
Φ_{ij}^{rad}	net radiation flux exchanged between particles Ω_i and Ω_j ....W

2. Theoretical treatments

2.1. Radiative heat transfer between particles in suspension

Radiative heat transfer is an energy exchange mode by emission and absorption of electromagnetic radiation. Its contribution is strongly related to the level of temperature.

The description and analysis of the radiation in granular media are based on two approaches commonly used in the literature. The first is a continuous approach; the granular medium is considered pseudo-homogeneous and radiation is studied by solving the equation of radiative transfer with respect to the boundary conditions on an absorbing, transmitting and diffusive medium [10]. This approach is valid when the particle sizes are larger than the wavelength of the radiation and the inter-particle distance. The second approach is non-continuous and is called "cell-model method". Radiation is treated as a local effect that stands between the surfaces bounding a unit cell and the surfaces of adjacent particles. While analyzing thermal transfer in packed beds, most previous studies were limited to heat transfer by conduction. Radiative transfer, when considered, is modeled with simplifying assumptions.

Based on the second approach, the net heat flux by radiation exchange from the difference of absorbed and emitted heat fluxes between two particles of the dust suspension, Φ_{ij}^{rad}, is calculated using the network method illustrated in Fig. 1. This method takes into account the surface resistances R_i and R_j which reflect the ability of the surface to radiate and the spatial resistances R_{ij}, R_{iR} and R_{jR} reflecting the ease of exchange between surfaces [5].

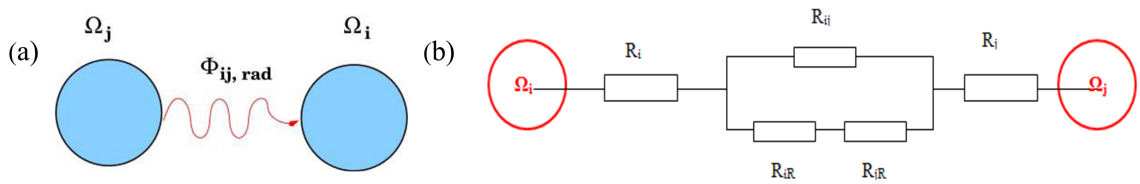


Fig. 1. (a) radiative exchange between two particles; (b) electrical analogy describing radiative heat exchange between two spherical particles.

The following assumptions are made:

- The particle diameter is larger than the wavelength of radiation ;
- The particle surface is gray emitting ;
- All particles are opaque solids.

$$\Phi_{ij}^{rad} = \frac{\sigma_s (T_i^4 - T_j^4)}{\left(R_i + \left(\frac{1}{R_{ij}} + \frac{1}{R_{iR} + R_{jR}}\right)^{-1} + R_j\right)} \tag{1}$$

Where:

- $R_i = \dfrac{1-\varepsilon_i}{\varepsilon_i A_i}$, $R_j = \dfrac{1-\varepsilon_j}{\varepsilon_j A_j}$, $R_{ij} = \dfrac{1}{A_i F_{ij}}$, $R_{iR} = \dfrac{1}{A_i F_{iR}}$ and $R_{jR} = \dfrac{1}{A_j F_{jR}}$;

- $F_{ji} = \frac{A_i}{A_j} F_{ij}$, $F_{ij} + F_{iR} = 1$ and $F_{ji} + F_{jR} = 1$.

2.2. Plane flame propagation in dust-air mixtures

Although in practical applications plane flames are not the common type, theoretical investigations have been concentrated essentially on plane flame models as they give simplicity in mathematical treatments. Among these theoretical investigations, those of Nusselt [11] were the pioneer to propose a thermal radiation theory of plane flame propagation in dust-air mixtures that was subsequently extended by Essenhigh and Csaba [6] to take into account the loss of heat by conduction from the dust particles to the ambient gas in the preheat zone of the flame. Later, Bhaduri and Bandyopadhyay [3] incorporated heat generation due to chemical reaction.

Essenhigh & Csaba [6] developed in 1963 a 1D theoretical model of a flame with a flat vertical front with invariant properties in the y and z planes at any x. A moving dust cloud travels the preheat zone in the direction of the flame front at initial velocity, temperature and concentration that vary when the gas expands (Fig .2). Emitted, scattered and reflected radiations from the particles are assumed to be negligible.

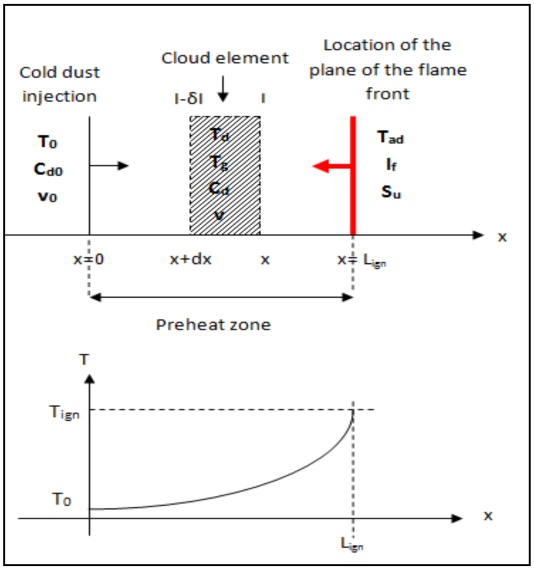


Fig. 2. Schematization of a cloud element in the preheat zone of the flame. Temperature curve of dust is also shown.

The physical behavior of the system is governed by three equations: the heat radiation from the flame to the dust (equation 2a), the rate of rise of gas and particles temperatures (equation 2b) and the heat loss by conduction from the dust to the ambient air (equation 2c):

$$\frac{dI}{dx} = kI = \frac{1}{v}\frac{dI}{dt} \tag{2a}$$

$$\frac{dI}{dx} = C_d C_p \frac{dT_d}{dt} + \rho_g C_{pg} \frac{dT_g}{dt} \tag{2b}$$

$$\frac{dT_g}{dt} = \frac{4\pi\lambda_g}{\rho_0 C_{pg} r_p}(T_d - T_g) \tag{2c}$$

Where:

- $C_d = C_{d0}\frac{T_0}{T_g}$, $v = v_0 \frac{T_g}{T_0}$ and $\rho_g = \rho_0 \frac{T_0}{T_g}$;

- $k = \dfrac{3C_{d0}}{4r_p\rho_p}$ is the absorption coefficient ;
- $m = kv_0$ and $K = \dfrac{3\alpha_g C_{d0}}{r_p^{\,2}\rho_p}$;
- $n = K(1 + \dfrac{\rho_0 C_{pg}}{C_{d0}C_p})$;
- $t_{ign} = \dfrac{L_{ign}}{v_0}$.

With mathematical arrangement, the system is reduced to two differential equations as follows:

$$\frac{m}{v_0} I_f e^{m(t-t_{ign})} = C_{d0}C_p \frac{dT_d}{dt} + \rho_0 C_{pg}\frac{dT_g}{dt} \tag{3a}$$

$$\frac{dT_g}{dt} = K(T_d - T_g) \tag{3b}$$

The equations (3a) and (3b) are solved simultaneously with respect to boundary conditions:

- at $t = t_0$, $T_d = T_g = T_0$;
- at $t = t_{ign}$, $I = I_f$ and $T_d = T_{ign}$.

When particles' temperature reaches ignition, an expression of the flame speed is provided:

$$S_u = \frac{I_f(1-e^{-mt_{ign}})}{(T_{ign}-T_0)C_{d0}C_p}[1 + \frac{K-n}{m+n}(1+\frac{1-e^{-nt_{ign}}}{1-e^{mt_{ign}}}\frac{m}{n})] \tag{4}$$

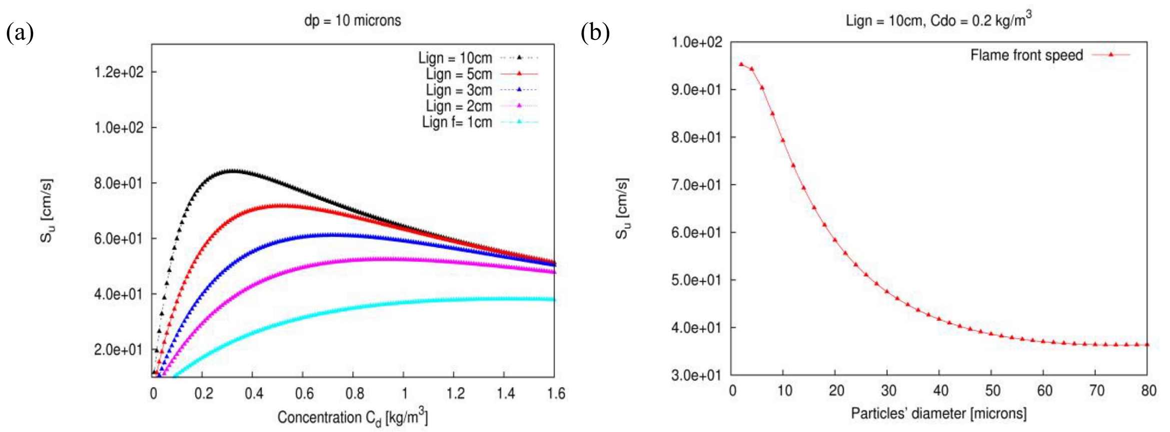


Fig. 3. (a) Variation of flame speed with dust concentration showing the influence of the finite ignition distance; (b) Variation of flame speed with particles' diameter for a concentration of 0.2 kg.m^{-3}

Fig. 3 shows that flame speed depends on dust concentration and drops when the ignition distance is reduced. It also decreases when the particles' diameter increases. The exponential term creates a peak in the flame speed curve. As the ignition distance diminishes, this peak drops in value and is displaced in the fuel-rich direction.

3. Simulation results

The proposed results are obtained with the DEM code MULTICOR developed at the LTI laboratory [7]. Dust particles are considered as discrete elements. The first calculations are dedicated to the modelling of radiative heat transfer between dust cloud particles. In a second step, heat transfers between dust and gas in the preheat zone of the flame are modeled.

3.1. DEM modelling of radiative heat transfer

Each dust particle emits radiation which is absorbed by directly neighboring particles. The corresponding equation of heat transfer is expressed for each particle as follows, considering that the variation of particle's temperature is caused only by the contribution of radiative transfer.

$$\rho_i V_i C_{pi} \frac{dT_i}{dt} = \sum_{j=1}^{n} \Phi_{ij}^{rad} \tag{5}$$

Where ρ_i is the density of the particle Ω_i, V_i is the volume of the particle Ω_i, C_{pi} is the constant pressure specific heat of the particle Ω_i and n is the number of the neighboring particles.

The discretization of equation (5) with respect to time leads to the calculation of the temperature at time t+Δt:

$$T_i^{t+\Delta t} = T_i^t + \frac{\Delta t}{\rho_i V_i C_{pi}} \sum_{j=1}^{n} \Phi_{ij}^{rad} \tag{6}$$

Fig. 4 details the 2D discrete model simulation of a granular medium of 10000 spherical discrete elements distant of 40 μm from each other. A heat source at 2500°K is initially located at the center of the right end of the domain. As shown, the rise of the particles' temperature contributes to the flame propagation process.

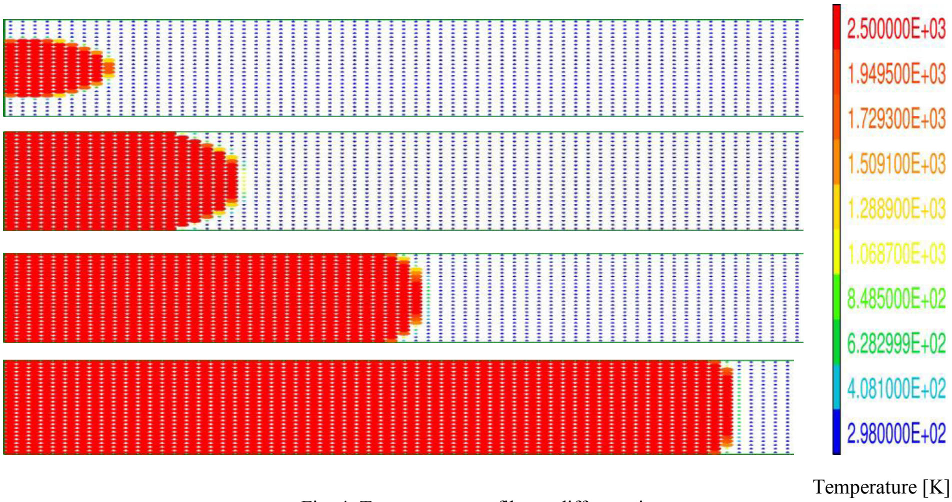


Fig. 4. Temperature profiles at different times

3.2. DEM modelling of the preheat zone of a flame propagating in dust-air mixtures

The same physical problem described in paragraph 2.2 is reproduced with DEM simulation as detailed in Fig. 5. The cold dust cloud emerges at initial velocity v_0 (= 50 cm.s^{-1}), temperature T_0 (= 298 °K) and concentration C_{d0} (C_{d0} varies from 0.1 kg.m^{-3} to 0.6 kg.m^{-3}). As dust particles (d_p = 10 μm) travel the preheat zone (L_{ign} = 10 cm) approaching the flame front (T_{ad} = 1773 °K), they absorb heat predominantly by radiation from the flame and lose heat by conduction to the surrounding ambient air. When they reach the ignition temperature, the flame front changes its physical position x_f. Relative motion between the particles and the surrounding gas may be neglected.

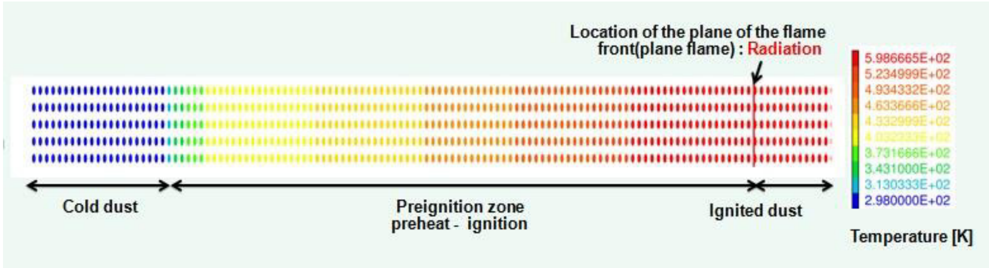


Fig. 5. Temperature profile of the dust cloud

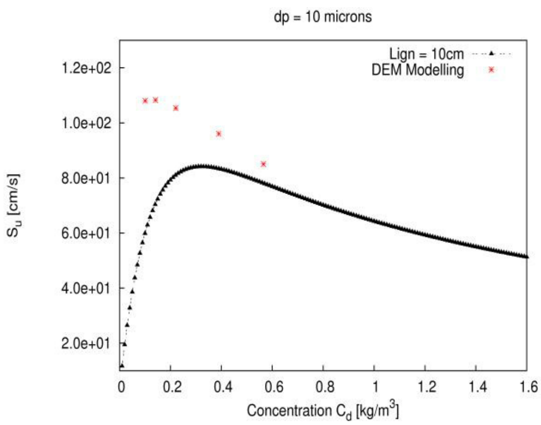
The discretization of equations (2b) and (2c) with respect to time, using mathematical arrangement of equation (2a), leads to the calculation of the dust and air temperatures at time t+Δt:

$$\mathrm{T}_d^{\,t+\Delta t} = \mathrm{T}_d^{\,t} + \Delta t \frac{4\pi\lambda_g}{C_{d0} C_p r_p}(T_g - T_d)^t + \Delta t \frac{k}{C_{d0} C_p} I_f e^{k(x-x_f)} \quad (7a)$$

$$\mathrm{T}_g^{\,t+\Delta t} = \mathrm{T}_g^{\,t} + \Delta t \frac{4\pi\lambda_g}{\rho_0 C_{pg} r_p}(T_d - T_g)^t \quad (7b)$$

The results obtained after the implementation of this model at the DEM code MULTICOR are given by Fig. 6:

(a)



(b)

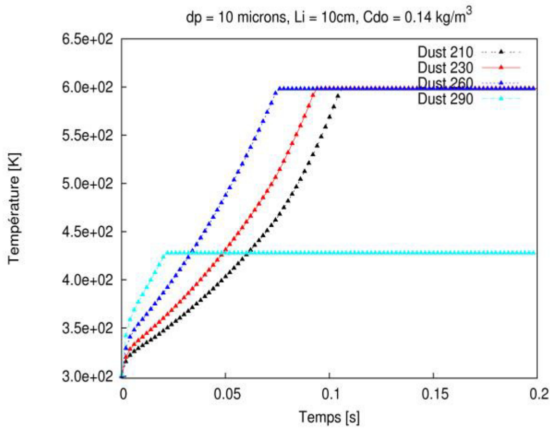


Fig. 6. (a) Comparison between analytical and numerical flame speeds; (b) Variation of dust temperature with time for different dust particle positions

While comparing the numerical and analytical flame speeds, differences are obtained. Even though both of them are at the same range, the differences are due to the fact that DEM modelling takes into account the thermal heat exchanged between each particle and its surrounding air which could not be provided by the analytical approach.

4. Conclusion

The theoretical model reproduced numerically is that of a plane flame front propagating through a mono-disperse and premixed dust cloud [6]. The flame propagation mechanism is the radiant heating to ignition of the dust cloud contained in the preheat zone. The ignition temperature is assumed to be constant and heat generation due to chemical reaction is not incorporated yet.

The flame speed depends on the dust concentration and decreases when the diameter of dust particles increases. As the ignition distance (or ignition time) drops, so does the flame speed.

Under this work, it was shown that DEM modelling could be an alternative for dust flames simulation. Further development will be carried out in order to model additional complex phenomena such as light scattered by small dust particles that should be taken into consideration seen the size of the particles and reaction mechanism in the combustion zone.

Acknowledgements

This study is carried out under RADIAN project (2013-2016). The authors would like to thank the "Région de Picardie" for its financial support.

References

[1] Benedetto A Di., & Russo P. (2007). Thermo-kinetic modelling of dust explosions. J. Loss Prev. Process Ind., vol. 20, pp. 303-309.
[2]Benedetto A Di., Russo P., Amyotte P., & Marchand N. (2010). Modelling the effect of particle size on dust explosions. Chemical Engineering Science, vol. 65, pp., 772-779.
[3] Bhaduri D., & Bandyopadhyay S. (1971). Combustion in coal dust flames. Combustion and Flame, vol. 17, pp., 15-24.
[4] Cashdollar K L. (2000). Overview of dust explosibility characteristics. J. Loss Prev. Process Ind., vol. 13, pp. 183-199.
[5] Cheng G J., & Yu A B. (2013). Particle scale evaluation of the effective thermal conductivity from the structure of a packed bed : Radiation heat transfer. Industrial & Engineering Chemistry Research, vol. 52, pp., 12202-12211.
[6] Essenhigh R H., & Csaba J. (1963). The thermal radiation theory for plane flame propagation in coal dust clouds. High Temperature Spectroscopy, pp., 111-124.
[7] Fortin J., Millet O., & De Saxcé G. (2004). Numerical simulation of granular materials by an improved discrete element method. International Journal of Numerical Methods in Engineering, vol. 62, pp. 639-663.
[8] Gao W., Mogi T., Sun J., Yu J., & Dobashi. (2013). Effects of particle size distributions on flame propagation mechanism during octadecanol dust explosions. Powder Technology, vol. 249, pp., 168-174.
[9] Huang Y., Risha G A., Yang V., & Yetter R A. (2007). Combustion of bimodal nano/micron-sized aluminum dust in air. Proceedings of the Combustion Institute, vol. 31, pp., 2001-2009.
[10] Jones P D., McLeod D G., & Dorai-Raj D E. (1996). Correlation of measured and computed radiation intensity exiting a packed bed. J. Heat Transfer, vol. 118, pp., 94-102.
[11] Nusselt W (1924). Verein Deutscher Ingenieure, pp., 124 and 129.
[12] Proust C. (2006). Flame propagation and combustion in some dust-air mixtures, J. Loss Prev. Process Ind., vol. 19, pp. 89-100.
[13] Proust C., Guessasma M., Saleh K., Fortin J. (2013). Amplification des effets des explosions sous l'effet du rayonnement thermique. Récents Progrès en Génie de Procédés, Numéro 104.